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EFFECT OF GROUND WATER ON STABILITY OF SLOPES AND STRUCTURES ERECTED ON THEM ON THAWING OF FROZEN SOILS

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13. ABSTRACT

From many years' investigations of the stability of soil masses and structures on the solifluction slopes of Chukotka, it has been established that the stability reserve coefficient of the thawed layer can in no way be determined on the basis of only the physico-mechanical properties and displacement parameters of the soils. To a considerable extent, the stability of soil masses is determined by their filtration qualities and specific conditions of slope flooding caused by the freeze-thaw cycles. The stability of the seasonally thawed layer on the slopes formed of silty sands and sandy loams is usually disrupted during prolonged rains. The loams and clays start to move even without atmospheric precipitation, owing to the ground water forming during thawing of interbeddings of segregated ice. Here the typical conditions for the stability of wet soils lying on the surface of frozen ground are examined.

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NOTICE

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From many years' investigations of the stability of soil masses and structures on the solifluction slopes of Chukotka, it was established that the stability reserve coefficient of the thawed layer can in no way be determined on the basis of only the physico-mechanical properties and displacement parameters of the soils. To a considerable extent, the stability of soil masses is determined by their filtration qualities and specific conditions of slope flooding caused by the freeze-thaw cycles.

Stability of the seasonally thawed layer on the slopes formed of silty sands and sandy loams is usually disrupted during prolonged rains. The loams and clays start to move even without atmospheric precipitation, owing to the ground water forming during thawing of interbeddings of segregated ice.

In the present report, we examine the typical conditions for the stability of wet soils lying on the surface of frozen ground.

Conditions of Stability of Moist Viscous-Plastic Soils in Absence of Freely Filtering Water

The determination of the stability of the active layer over the sloped surface of frozen ground is a specific case of the problem involving the stability of a slope when the position of the sliding surface is known. At unlimited length of slope, we can assume the condition of a plane problem; the sliding surface will then be portrayed by a chain line aa'b'd' (Fig. 1, position 1).

Segment aa' represents the separation line.

Segment a'b' represents the actual sliding surface.

Segment b'd represents the critical position of soil flow prism.

In the absence of gravity water, the stability reserve factor of the slope can be found with the formula:

$$K_{nn} = \frac{\tau_c \ell + E_n + F_p}{\tau \cdot \ell} = \frac{\tau_c}{\tau} + \frac{E_n + F_p}{\tau \ell} \qquad (1)$$

where: $\tau = \gamma \cdot H \cdot \cos \alpha$ = shear stress; $\tau_c = C_T + \gamma_T \cdot \cos \alpha \cdot \tan \varphi_T$ = resistance of thawed soil to displacement on slipping on frozen soil surface; F_p = resistance of soil in thawed layer to erosion (force required for washing a 1 m wide strip of the thawed layer); γ_T, C_T, and φ_T = the volumetric weight, viscosity and internal friction angle of thawed layer, respectively;

E_n = [illegible]

= passive pressure (resistance) of soil; and ℓ = length of slipping line a'b' which in case of critical equilibrium (at $k_{nn} = 1$) is determined from the expression:

$$\ell_{np} = \frac{E_n + F_p}{\gamma_T H \cdot \sin \alpha - (C + \gamma_T H \cdot \cos \alpha \cdot \tan \varphi_T)} \qquad (2)$$

In Eq. (2), the H-value signifies that thickness of active layer at which movement of the viscous-plastic medium begins at given steepness of the slope. Its value can be found from the equation of a viscous-plastic medium (Shvedov-Bingham equation):

$$\tau = \tau_{np} + \eta \frac{dv}{dy}, \qquad (3)$$

where: τ = shear stress; τ_{np} = critical shear resistance, equalling the stress at which the nondamping plastic deformations of the soil begin; η = coefficient of viscosity; dv/dy = velocity gradient according to depth of moving layer.

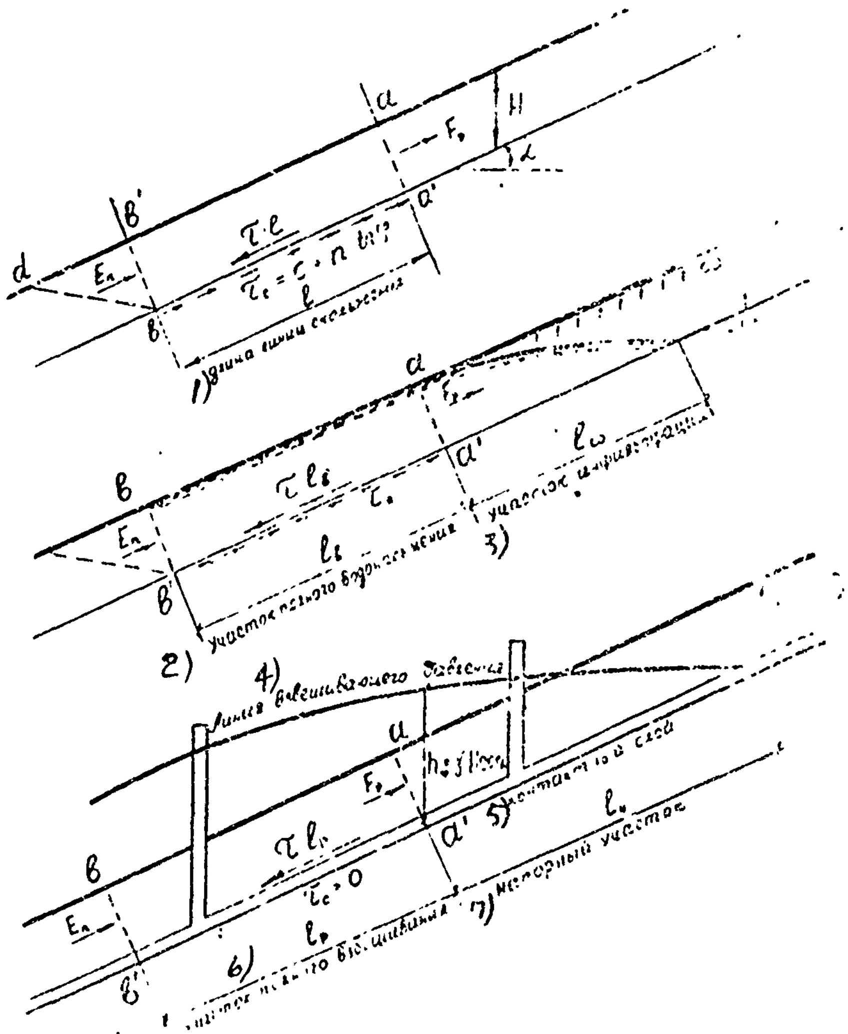

Fig. 1. Determination of Stability of Active Layer Lying on Inclined Surf ce of Frozen Ground: 1- in absence of filtration flows; 2- at complete water saturation of thawed layer by nonpressurized filtration flow; and 3- at total suspension of thawed layer by pressure filtration flow in contact layer. Key: 1) length of slip line; 2) Sector of comp e.e water saturation; 3) Infiltration sector; 4) Line of suspending pressure; 5) Contact layer; 6) Total suspension sector; and 7) Pressure sector.

The velocity gradient dv/dy indicates that the mutual displacement of soil layers is possible at dv/dy > 0 or $\tau - \tau_{np} > \theta$. i.e. at $\tau - \tau_{np}$.

In the absence of a useful load, the shear stress on a slope is caused only by the soil's own weight and is determined with the equation:

$$\tau = \gamma_T \cdot H \cdot \sin\alpha$$

where γ_T = soil's weight by volume; H = thickness of thawed layer; and α = slope's angle of incidence.

The condition of critical equilibrium of a viscous-plastic medium is obtained from Eq. (3) at dv/dy = θ and after the substitution of the τ-value from Eq. (4), it permits us to determine the maximum permissible height of H-layer at which the slope's stability is retained:

$$H_0 = \frac{\tau_{np}}{\gamma_T \cdot \sin\alpha}. \qquad (5)$$

Stability Conditions of Excellently-Filtering Thixotropic Soils at Complete Water Saturation by Non-ramming Ground Water

Shear stress τ in a state of critical equilibrium equals the soil's shearing strength:

$$\tau_c = C + P_{эф}\, tg\, \varphi, \qquad (6)$$

where C = structural adhesion; $P_{эф}$ = effective normal pressure on sliding surface (is transmitted only through the soil's rigid skeleton); and φ = angle of internal friction.

If the soil is not water-soaked, the pressure from the soil's own weight is transmitted entirely via the rigid skeleton, i.e.:

$$P_{эф} = P = \gamma H \cos\alpha = \Delta \cdot H \cdot \cos\alpha \qquad (7)$$

If the soil is completely water-soaked, effective pressure P' decreases according to the Archimedes Law by an amount equalling the weight of the forced-out liquid in the soil skeleton's volume and is ascertained with the formula:

$$P'_{эф} = \frac{\Delta - \gamma_B}{1 + \varepsilon} H \cdot \cos\alpha, \qquad (8)$$

where: Δ and γ_B = specific weights of soil skeleton and water; ε = porosity factor; and α = slope's angle of inclination.

With a decrease in the effectiveness of pressure $P_{эф}$, according to Eq. (6), the shear resistance τ_c decreases. Simultaneously, as a result of the pores' filling with water, the soil's

weight density increases and there is a concomitant increase in the shear stress. Consequently the complete water saturation of the soil simultaneously with a decrease in resistance to friction increases the sheer stresses, thus lowering its stability as compared with that of the soil not saturated with water.

At complete water saturation of the thawed layer lying on the inclined surface of frozen soil, the reserve stability factor k_B with consideration of Eqs. (1, 6, 7 and 8) can be determined as (Fig. 1, position 2):

$$K_B = \frac{C + \frac{\Delta - \gamma_B}{1+\varepsilon} H \cos\alpha \cdot tg\,\varphi}{\frac{\Delta + \gamma_B \varepsilon}{1+\varepsilon} \cdot H \cdot \sin\alpha} + \frac{E_n + F_p}{\frac{\Delta + \gamma_B \varepsilon}{1+\varepsilon} H \cdot \sin\alpha \cdot \ell} \tag{9}$$

At complete water saturation the shifting of the thawed layer is possible at $H > h_{kp}$ where h_{kp} = critical depth of water-soaked layer determined with the formula:

$$h_{kp} = \frac{C\,(1+\varepsilon)}{(\Delta + \gamma_B \varepsilon) \cdot \sin\alpha - (\Delta - \gamma_B) \cdot \cos\alpha \cdot tg\,\varphi_r} \tag{10}$$

The length of slipping line ℓ_B in a state of critical equilibrium is determined from Eq. (9) at ($K_B = 1$):

$$\ell_B = \frac{E_n + F_p}{\frac{\Delta - \gamma_B \varepsilon}{1+\varepsilon} \cdot H \cdot \sin\alpha - \left(C + \frac{\Delta - \gamma_B}{1+\varepsilon} \cdot H \cdot \cos\alpha \cdot tg\,\varphi\right)} \tag{11}$$

On the sectors of the slope with complete water saturation, the rain does not seep in; the water runs over the surface. However, the complete water saturation of the thawed layer is possible provided that the length of slope above the sector with complete water saturation is not less than the value termed by us as the length ℓ_ω of infiltration sector and being determined by the expression:

$$\ell_\omega = \frac{K_\varphi \, h_{kp} \, tg\,\alpha}{\omega}, \tag{12}$$

where: K_φ = filtration coefficient of thawed soil in direction of slope's fall; and ω = rate of rainwater's infiltration.

In this manner, the stable length of slope $L_{уст}$ equals the sum of lengths of slipping line ℓ_B and the length ℓ_ω of infiltration sector:

$$L_{уст} = \ell_B + \ell_\omega. \tag{13}$$

At total water saturation, the soils' stability on a slope is 1.5-2 times less than in its absence. The movement of soils on a slope in the case of complete water soaking of the thawed layer by nonpressurized water becomes possible if the thickness of the thawed water-soaked layer and length of slope exceed their own critical values h_{kp} and L_{ycT} . If the thickness of thawed layer is less than h_{kp}, while the length of slope or bank is less than L_{ycT} , the slope's stability is assured.

The proximity of the frozen soils' surface, comprising a water obstacle in the regions with seasonally- and permanently-frozen soils, greatly facilitates the water soaking of the upper thawed layer, often leading to landslides.

Landslides on the banks of large excavations sometimes occur quite intensively and cause much trouble to the road builders. Thus, in one excavation dug in silty loams with a 15-20% content of ballast, after some rains the bank soil slid down and buried the road.

The essential method of counteracting the slides is the proper organization of drainage, precluding the water saturation of soil on the slopes and banks. The distance between the drainage ditches based on dip of bank should not be more than 0.7 L_{ycT}. In the regions with seasonally frozen soils, it is quite effective to reinforce the banks with tree and bush plantings.

Stability Conditions of Poorly Filtering Plastic Soils Suspended by Pressure Ground Water

The stability of weakly-filtering loams on slopes containing permafrost soils is determined to a considerable extent by the pressure of ground water circulating in the active layer. The appearance of a pressure filtration flow on a slope is associated with the presence of water resistance from beneath (surface of frozen soils) in combination with the well-filtering inclined level and ground water supply sources.

A well-filtering inclined level is formed on thawing of frozen soils owing to the fact that the structure of the active layer on the slopes in the occurrence regions of the permanently frozen cohesive soils is quite unique. The ice content in it varies by depth: in the upper part, it is relatively slight (20-25%), in the central part, it reaches 10-15%, while in the lower part near the seasonal thawing boundary, it increases sharply to

30-70%. The cryogenic texture of this layer is usually latticed—the soil aggregates are separated from each other by vertical and horizontal ice interstratifications.

After thawing, the soils have many pores and cracks intersecting them in the most diverse directions and the soils come to resemble ordinary ballast. Such a structure of the thawed layer at the contact with the frozen layer (for brevity, we will simply refer to it as the contact layer)(Fig. 1, position 3) increases its porosity abruptly and hence there is also a sharp increase in the filtration factor as compared with the thawed middle layer where after thawing, the soil retains its monolithic state and the postcryogenic texture has managed to crumble.

The increase in the soils' water permeability after their freeze-thaw cycle is proved in the reports prepared by N.A. Tsytovich (1955), G.D. Potrashkov and L.N. Krustalev (1961). According to their data, the water permeability of soil after thawing increases by more than $1 \cdot 10^3$ times owing to the retention of the postcryogenic texture.

Consequently at the end of summer on the slopes containing permanently frozen deluvial loams, in the lower part of the active layer, a well-filtering inclined level forms; it is mantled by the thawed layer, the water perviousness of which is negligibly slight.

The supply source for the ground water is comprised of the icy interbeddings or infiltration water. At thawing of the icy interstratifications, part of the water is used in the hydration of the soil aggregates and seeps into them. The remaining water acquires the ability to move over the contact layer along the slope. This is favored by the inclined position of the contact layer.

The contact layer is not stable since the soil aggregates gradually disintegrate as a result of hydration. In proportion to the soil's thawing, more and more new layers become formed with an increased filtration factor; these layers replace the disintegrating layers. Therefore the contact layer, in spite of the aggregates' continuous breakdown, is preserved in the lower part of the active layer throughout the ice level's thawing period.

In this manner, during the thawing on the slopes, conditions are created for the origination of pressure-type filtration flows, significantly reducing the active layer's stability.

At complete suspension of the thawed layer, the thawed layer's shear resistance along the frozen soil's surface equals 0; therefore, the stability reserve factor is determined with the formula:

$$K_H = \frac{E_n + F_p}{\gamma_T \cdot H \cdot \sin\alpha \cdot \ell_p} . \tag{14}$$

The maximum permissible length ℓ of the totally suspended sector is determined from Eq. (14) at $K_H = 1$ (Fig. 1, position 3). The total length L_{ycT} of the stable part of the active layer in the presence of suspending pressure in the contact layer is determined with the formula:

$$L_{ycT} = \ell_H + \ell_p , \tag{15}$$

where: L_{ycT} = length of slope's stable part; ℓ_H = length of pressure sector on slope, on which the pressure increases in the contact layer from zero to γ_r Hcosα ; and ℓ_p = length of suspended sector of slope, i.e. the maximally possible length of the completely or partly suspended sector at the time of its separation prior to sliding.

The values for ℓ_H and ℓ_p can be determined from the formulas proposed by the author:

$$\ell_H = \frac{\sin\alpha \pm \sqrt{\sin^2\alpha - 2\left(\frac{q}{K_K \Omega_K} - \mu \frac{\Psi}{H \Omega_K} h_{np}\right) \ell_p}}{\frac{q}{K_K \Omega_K} - \mu \frac{\Psi}{H \Omega_K} h_{np}} \tag{16}$$

$$\ell_p = \frac{E_n + F_p}{\gamma_T \cdot H \cdot \sin\alpha} , \tag{17}$$

where

$$q = V_{np} \cdot S \cdot i \cdot K_B \qquad \mu = \frac{K_\Phi}{K_K}$$

In the expressions indicated, along with the notations used earlier, we have adopted the following standard symbols: q = excess amount of water forming on thawing of icy soil, per unit of slope's area; i = ice content; K_k and K_Φ = coefficients of filtration in contact and thawed layer; μ = ratio K_Φ / K_k of filtration coefficients; Ω = cross section of contact layer; h_{np} = suspending pressure in contact layer; E_n = passive pressure (resistance) of

small layer; K_β = coefficient of water yield from frozen soil on its thawing: F_p = rupture resistance of sod cover; and φ_T , C_T , and γ_T = angle of internal friction, structural adhesion and volumetric weight of thawed layer.

Until the present time, in determining the stability of the active layer on the slopes and banks, we did not consider the possibility of the suspending pressure's appearance. Based on our investigations in Chukotka, it was established that on the slopes composed of soils with filtration coefficients less than $1 \cdot 10^{-4}$, the appearance of suspending pressure in the contact layer is inevitable. Moreover, the stability factor of the thawed layer's suspended sectors as compared with the sectors where suspension is lacking decreases by 3-5 times.

The underestimation of this factor in planning and building the road embankments and other structures has often led and is now leading to the sliding and disruption of structures in the suspended sectors. Thus the author has observed instances of the sliding of road embankments by 50 m and 150 m downslope. This was caused by the fact that in the surveying and planning stages, it was overlooked in the calculations that on certain sectors of the slope, the active layer at the end of summer is in an unstable state, even under natural conditions. The loading of these unstable sectors with the weight of the fill sharply increases the tangential stresses along the base of the thawed layer and it slides together with the structure built on it.

In this way, the presence of nonpressurized and particularly of pressurized ground water reduces significantly the stability of the active layer on the slopes and declivities. For a proper appraisal of the conditions and the provision of stability to the slopes and structures, on the inclines in the permafrost soil regions, in the process of surveying for construction, along with the determination of the standard parameters (physico-mechanical properties of soils, seasonal thawing depth, etc.), it is also necessary to ascertain:

on the slopes formed of slightly-filtering-loams--the value for the maximal hydrostatic pressure in the contact layer and the length of the slope's stable part; and

on the slopes formed of silty sands and light fairly water-permeable sandy loams, the possibility of their complete water saturation in the periods with maximal amount of precipitation at critical values for the thawed layer's thickness and length of slope or bank.

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